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## **Stable Dielectric Gratings Implemented by Composition Striations in Paraelectric Crystals**

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### ***Abstract***

Electrically controlled Bragg gratings (ECBG) implemented by periodic striations produced during the crystal growth process are demonstrated in doped potassium sodium tantalate niobate crystals and potassium lithium tantalate crystals. The periodic striations induce a spatial modulation of the low frequency dielectric. The application of a uniform electric field produces an induced polarization grating. The latter induce an electrically controlled birefringence grating through the electrooptic effect.

### **Introduction**

A method for implementing an electrically controlled Bragg grating (ECBG) by the introduction of a periodic spatial variation of the composition in paraelectric Perovskites is presented. This method opens the way for a family of light controlling devices that can be operated at both the visible and near IR wavelengths without inflicting optical damage, and can be stored at very high temperatures.

Electroholography (EH) is an optical switching method based on electrical control of the reconstruction process of volume holograms (REF 1,2 & 3). In particular it was shown that the EH switching method is very effective in wavelength division multiplexing (WDM) networks, where it is required to selectively manipulate the single wavelength channels of the WDM lightwave (REF 4). The basic building block of the EH device is the electrically controlled Bragg grating (ECBG) illustrated schematically in Figure 1. When the electric field is turned off, the grating is in its latent state. In this state (Figure 1a), the grating is transparent so that the incident lightwave propagates through the grating unaffected. When the electric field is turned on (Figure 1b), the grating is activated. In the 'on' (active) state an input beam will be diffracted provided it fulfills the Bragg condition (the beam at wavelength  $\lambda_1$  in Figure 1b). An input beam that does not fulfill the Bragg condition will propagate through the active grating unaffected (the beam at wavelength  $\lambda_2$  in Figure 1b). Thus, electrically controlled gratings possess the basic features for functioning as wavelength selective switches.

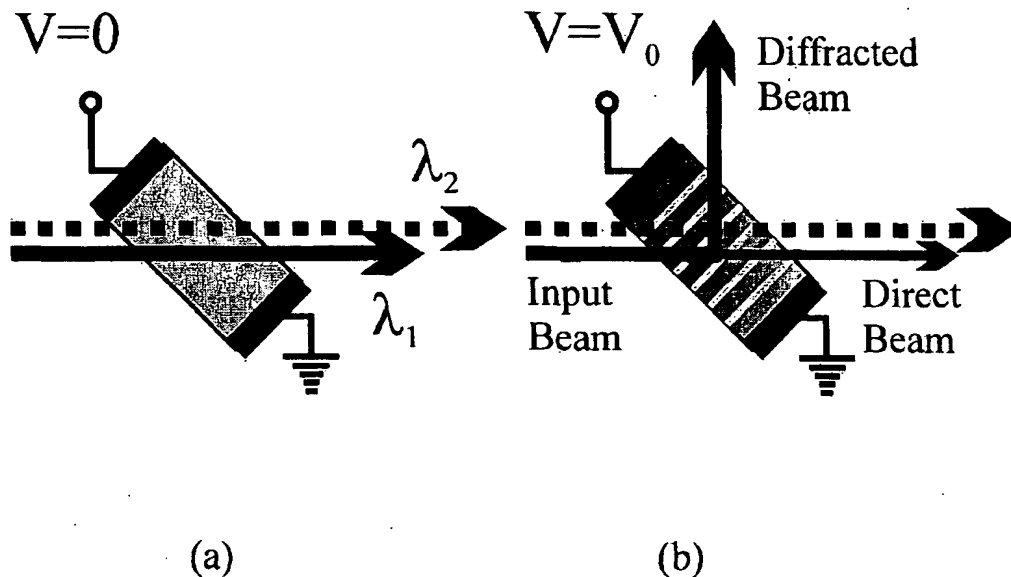


Figure 1: An electrically controlled Bragg grating. (a) In the 'off' state; (b) In the 'on' state.

ECBGs are implemented by exploiting the voltage controlled photorefractive effect in paraelectric crystals (REF 5 & 6). Here the ECBG is implemented as a spatial distribution of space charge produced optically by the PR process. The polarization grating induced by the space charge field is latent, namely it is transparent to the reconstruction beam. An electric field applied to the crystal couples with the space charge grating and induces a birefringence grating through the quadratic electrooptic effect.

The reliability of ECBGs that are based on the voltage controlled photorefractive effect depends on the stability of the space charge grating. The latter is subject to two erasure mechanisms: erasure during readout and thermal erasure. Erasure during readout occurs when the space charge is illuminated by photons that photo-excite the trapped charges that constitute the space charge. These become mobile and travel in a direction that causes gradual erasure of the grating. Thermal erasure occurs by the thermalization of charges that are trapped in shallow traps and once they become mobile travel in a direction that causes gradual erasure of the grating. These two processes are the main mechanisms that govern lifetime of the ECBG both during operation and storage. It is therefore desirable to be able to create an ECBG that is immune to these mechanisms. It will henceforth be shown that periodic modulation of the crystal composition that is produced during the growth of the crystal causes the formation of a permanent dielectric grating that induces a birefringence grating under the application of an electric field. These gratings are immune to optical damage and are thermally stable at elevated temperatures.

**Theoretical Basis of the Dielectric ECBG**

It is well established that the phase transition temperature  $T_c$  of paraelectrics is strongly affected by the presence of impurities and defects. For example, the replacement of a  $Ta^{+5}$  ion in potassium tantalate niobate (KTN) by an  $Nb^{+5}$  ion will cause a change in  $T_c$  of magnitude:  $\delta T_c = 8.5 \text{ K/1\% per mole } Nb^{+5}$  (REF 7). A similar effect can be achieved by replacing a  $K^+$  ion in KTN by either  $Li^+$  or  $Na^+$  (REF 8).

Consider a KTN crystal in which a periodic grating in the concentration of the niobium was generated during the growth of the crystal so that the relative concentration of the niobium ions is given by

$$\frac{[Nb^{+5}]}{[Nb^{+5}] + [Ta^{+5}]} = A \cdot \cos(\mathbf{K} \cdot \mathbf{x}) \quad [1]$$

where  $\mathbf{K}$  is the grating vector of the relative concentration and  $A$  is its amplitude. This concentration grating will create spatially correlated variations in the phase transition temperature that will result in a  $T_c$  grating given by

$$\delta T_c(\mathbf{x}) = \Delta T_c \cos(\mathbf{K} \cdot \mathbf{x}) \quad [2]$$

where  $\Delta T_c$  is the amplitude of the  $T_c$  grating. At the paraelectric phase, according to the Curie Weiss law, the  $T_c$  grating will yield a dielectric grating with spatial dependence given by

$$\delta \epsilon_r(\mathbf{x}) = \frac{-C}{(T - T_c)^2} \cdot \Delta T_c \cos(\mathbf{K} \cdot \mathbf{x}) \quad [3]$$

where  $C$  is the Curie constant and  $\epsilon_r$  is the relative (low frequency) dielectric constant. Applying a uniform electric field to the crystal will generate an induced polarization grating that is spatially correlated with the  $\delta \epsilon_r$  grating and is given by

$$\delta P(\mathbf{x}) = \epsilon_0 \delta \epsilon_r(\mathbf{x}) E_0 \quad [4]$$

where  $\epsilon_0$  is the dielectric permittivity. (It is assumed in [4] that the crystal is slightly above  $T_c$  so that  $\epsilon_r \gg 1$ ).

In general, at the paraelectric phase where the electrooptic effect is *quadratic*, the electric field induced birefringence is given by

$$\Delta n = -\left(\frac{1}{2}\right)n_0^3 g_{\text{eff}} P^2 \quad [5]$$

where  $n_0$  is the index of refraction at the paraelectric phase,  $g_{\text{eff}}$  is the effective quadratic electrooptic coefficient, and  $P$  is the induced (low frequency) polarization.

Thus, the application of a uniform electric field to a crystal containing a  $T_c$  grating will result in an ECBG of the form

$$\delta[\Delta n](x) = -\frac{n_0^3 g_{\text{eff}} \epsilon_0^2 \epsilon_r^2}{T - T_c} E_0^2 \cdot \Delta T_c \cos(\mathbf{K} \cdot \mathbf{x}) \quad [6]$$

where  $E_0$  is the applied electric field.

As an example, consider a KLTN crystal in which a  $T_c$  grating with a period spacing of  $1\mu\text{m}$  and amplitude of  $\Delta T_c = 1\text{K}$  was formed during the growth of the crystal. Assume a 3 mm thick sample is set in the configuration presented in Figure 2 in which the grating vector, the applied electric field, and the polarization of the input beam are parallel. For this configuration  $g_{\text{eff}} = 0.1 \text{ m}^4/\text{C}^2$ . Setting the crystal at  $T - T_c = 5^\circ\text{C}$ , and assuming  $\epsilon_r = 10^4$  and  $E_0 = 3.0 \text{ kV/cm}$ , will yield (according to [6]) a birefringence grating given by

$$\delta(\Delta n) = 2.92 \cdot 10^{-4}$$

It should be noted that alternatively the  $T_c$  grating can be generated by either the formation of  $[\text{Li}^+]/[\text{K}^+]$  concentration grating, or by formation of a  $[\text{Na}^+]/[\text{K}^+]$  concentration grating.

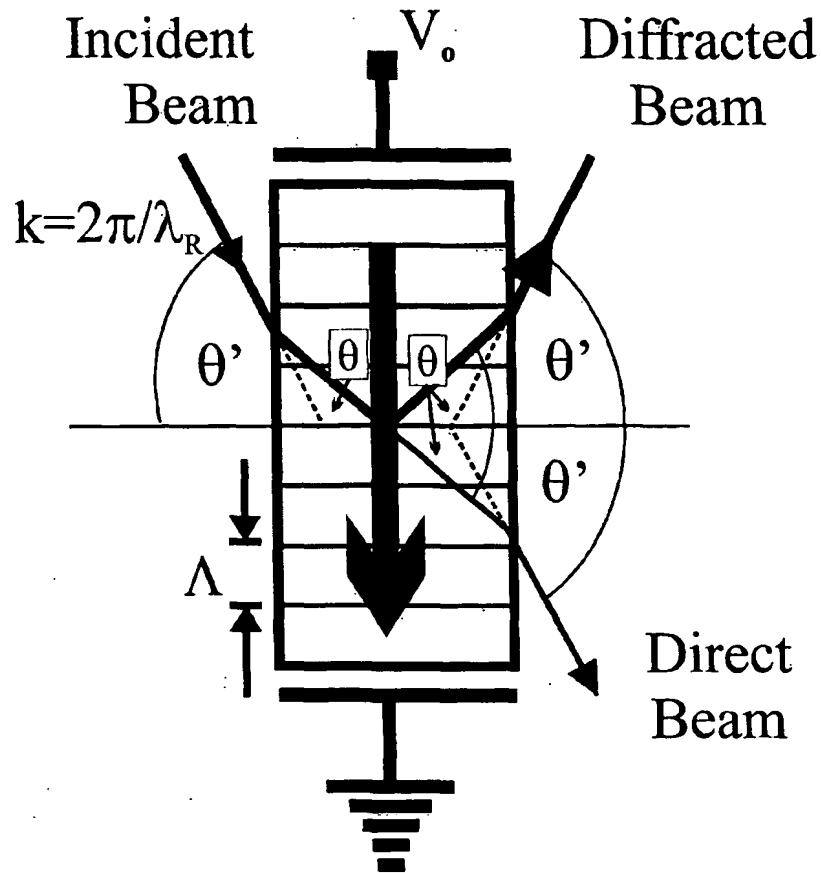


FIGURE 2. A Detailed description of the electrically controlled Bragg grating in the transmission symmetrical configuration.

### Implementation of the Striation Gratings

The  $T_c$  grating is generated during the growth of the crystal in the following manner: KTN, KLTN and KNTN are grown by the top seeded solution growth method. A cooled seed is immersed in a solution consisting potassium oxide as solvent and niobium oxide and tantalum oxide and solutes. The entire system is then cooled down slowly as the crystal grows on the interface between the seed and the flux. (A detailed description can be found in reference 9). The periodic modulation in the crystal composition (i.e. the striation grating) in the grown crystal is produced by creating a periodic modulation in the growth temperature that is superimposed with the cool-down of the system temperature. The procedure is illustrated schematically in figure 3 in which the phase diagram of KTN is presented.

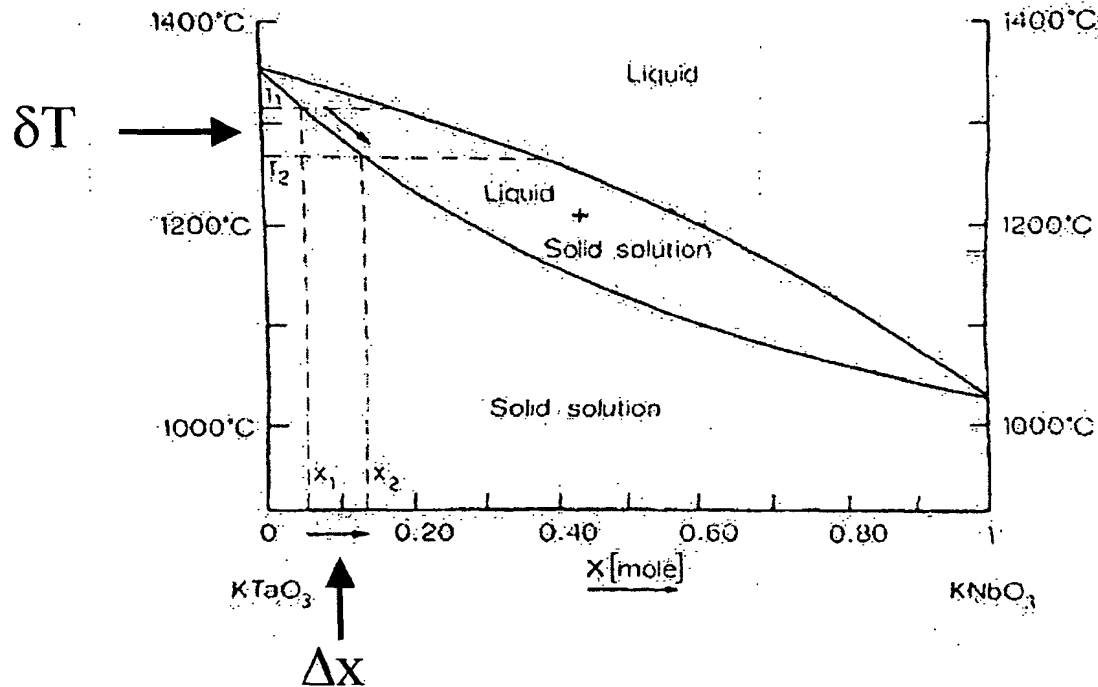


Figure 3: The phase diagram of KTN. It is shown the a change of  $\delta T$  during the growth will create a change of  $\Delta x$  in the composition of Nb/Ta ratio in the grown crystal.

### Method A:

In order to homogenize the flux during the growth, it is continually stirred by rotating the seed. It was shown in Ref. 9 that periodic reversals in the direction of rotation of the growing crystal cause the necessary perturbation in the flux temperature to induce the

formation of periodic striations. It was further shown in ref. 9 that the formed striation gratings are in fact a periodic modulation in the relative concentrations of the  $\text{Nb}^{+5}$  and the  $\text{Ta}^{+5}$  ions. Since the concentration of the  $\text{Nb}^{+5}$  ions determines the phase transition temperature, this process results in the formation of a  $T_c$  grating. The latter induces a grating of the dielectric through the Curie Weiss law according to equation [3]. Hence, if the crystal temperature is set to slightly above the phase transition temperature, the dielectric grating will be of significant magnitude.

#### **Method B:**

An alternative method for forming a striation grating is by rotating the seed around an off center axis in the crucible.

This method is illustrated schematically in figure 4.

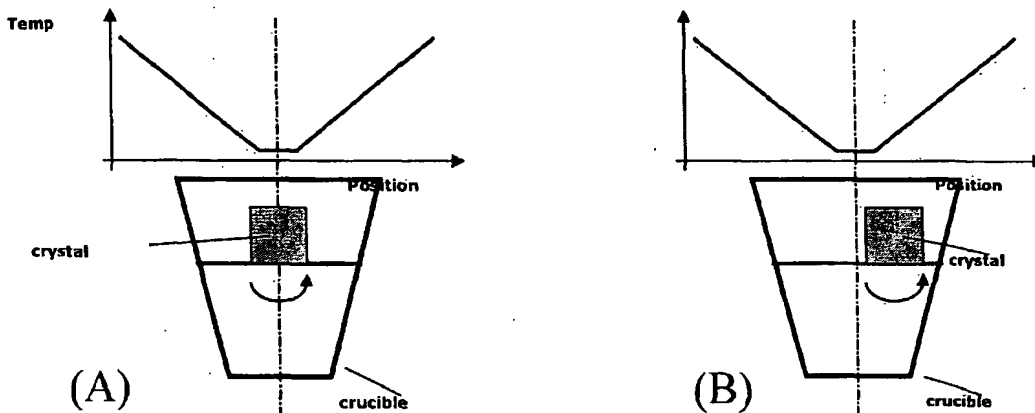


Figure 4: (A) Normal growth: The growth is done in the center of the crucible where the temperature is uniform; (B) The growth is done in an 'off center' position where the temperature varies along the radius of the crucible.

In a normal growth procedure the seed is rotating in the center of the crucible where the temperature is assumed uniform. However, it is known that the temperature of the flux increases radially, due to the fact that the crucible is heated by heating elements are positioned around it. This gradient in the temperature can be exploited to form the striation gratings. The rod that holds the seed is positioned in an off center position relative to the center of the crucible. In this position, as the growing crystal is rotated it is moved along the radial gradient of temperature in the crucible. Thus by rotation the growing crystal it is subjected to periodic modulation of the temperature which generate a striation grating.



## Preliminary experimental results

### Example 1:

Method B was used to produce a number of gratings with periods ranging from 0.2 to 10 microns. A striation grating grown by method B with period of approximately 0.5 microns is presented in figure 5.

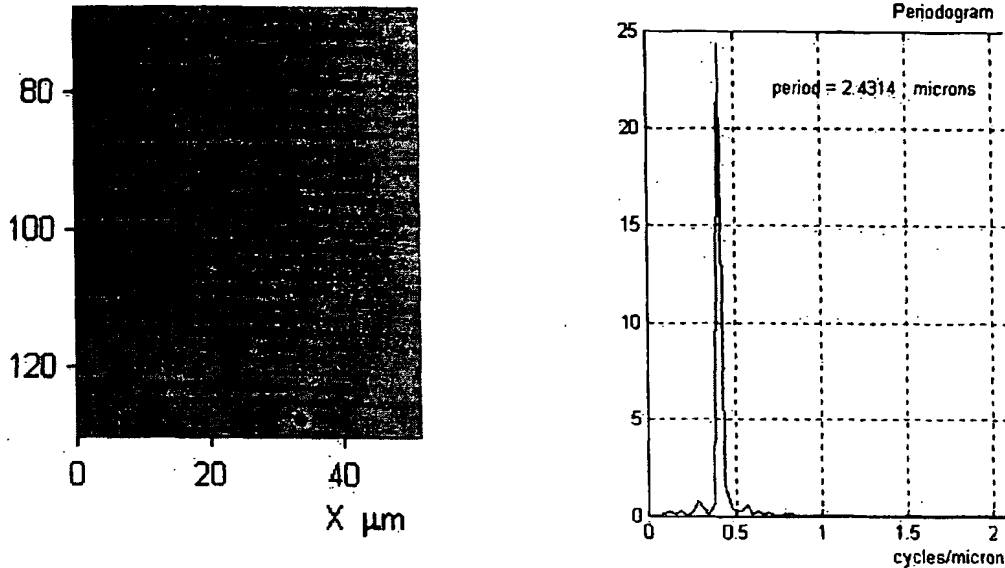


Figure 5: A striation grating grown by method B with a 0.4 micron period sampled by a differential interference microscope, and the fourier transform of the interference pattern.

### Example 2:

A KLTN crystal with a striation grating was grown using method A described above. The crystal phase transition temperature was  $T_c=18^\circ\text{C}$ , and the grating period was approximately  $10.2\text{ }\mu\text{m}$ . The diffraction was measured in the configuration illustrated in Figure 2. A probe beam at  $\lambda=1.31\text{ }\mu\text{m}$  was directed at the sample at  $7.5^\circ$  to its input surface, so that it was Bragg matched to the second harmonic of the grating. The beam crossed approximately 90 periods of the grating. Results of measurements of the diffraction efficiency as function of the applied electric field are presented in Figure 6 for a series of operating temperatures.

Note that the crystal generated a strong diffraction at  $E_0=0$ .

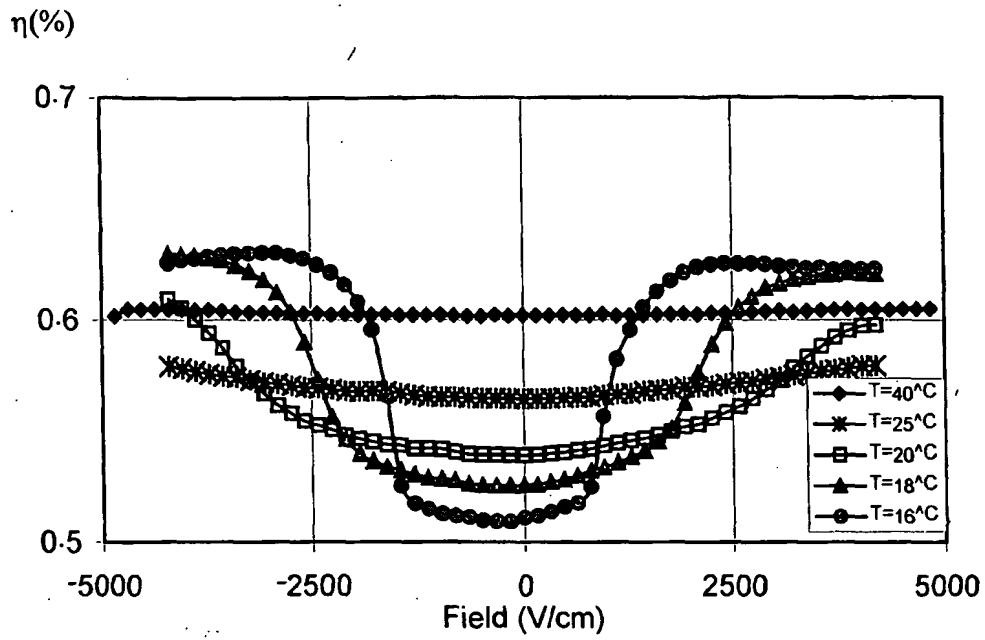


Figure 6: Diffraction efficiency vs. applied electric field of a striation grating in a KLTN crystal with  $T_c=18^{\circ}\text{C}$ .

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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT  
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08/04/03

Atty. Docket: AGRANAT1

INVENTOR(S)/APPLICANT(S)			
LAST NAME	FIRST NAME	MI	RESIDENCE (CITY AND EITHER STATE OR FOREIGN COUNTRY)
AGRANAT	Aharon	J	Mevasseret Zion, Israel
<input type="checkbox"/> Additional inventors are being named on separately numbered sheets attached hereto			
TITLE OF THE INVENTION (280 characters max)			
STABLE DIELECTRIC GRATINGS IMPLEMENTED BY COMPOSITION STRIATIONS IN PARAELECTRIC CRYSTALS			
CORRESPONDENCE ADDRESS			
Direct all correspondence to the address associated with Customer Number 001444, which is presently: BROWDY AND NEIMARK, P.L.L.C. 624 Ninth Street, N.W., Suite 300 Washington, D.C. 20001-5303			
ENCLOSED APPLICATION PARTS (check all that apply)			
<input checked="" type="checkbox"/> Specification (with Figures 1-6 incorporated within the specification)	Number of Pages	10	<input checked="" type="checkbox"/> Applicant claims small entity status. See 37 C.F.R. §1.27
<input type="checkbox"/> Drawing(s)	Number of Sheets		<input type="checkbox"/> Other (specify) _____
METHOD OF PAYMENT (check one)			
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The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

☒ No ☐ Yes, the name of the U.S. Government agency and the Government contract number are:

Respectfully submitted,

BROWDY AND NEIMARK, P.L.L.C.

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